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VEMAP vs VINCERA: A DGVM sensitivity to differences in climate scenarios

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ABSTRACT

The MC1 DGVM has been used in two international model comparison projects, VEMAP (Vegetation Ecosystem Modeling and Analysis Project) and VINCERA (Vulnerability and Impacts of North American forests to Climate Change: Ecosystem Responses and Adaptation). The latest version of MC1 was run on both VINCERA and VEMAP climate and soil input data to document how a change in the inputs can affect model outcome. We compared simulation results under the two sets of future climate scenarios and reported on how the different inputs can affect vegetation distribution and carbon budget projections. Under all future scenarios, the interior West becomes woodier as warmer temperatures and available moisture allow trees to get established in grasslands areas. Concurrently, warmer and drier weather causes the eastern deciduous and mixed forests to shift to a more open canopy woodland or savanna type while boreal forests disappear almost entirely from the Great Lakes area by the end of the 21st century. While under VEMAP scenarios the model simulated large increases in carbon storage in a future woodier West, the drier VINCERA scenarios accounted for large carbon losses in the east and only moderate gains in the West. But under all future climate scenarios, the total area burned by wildfires increased especially in C4 grasslands under all scenarios and in dry woodlands under VINCERA scenarios. The model simulated non-agricultural lands in the conterminous United States as a source of carbon in the 21st century under the VINCERA future climate scenarios but not VEMAP. However, the magnitude of this carbon source to the atmosphere could be greatly reduced if the CO_2 growth enhancement factor built in the model was enhanced but evidence that all mature forests across the entire country will respond positively to increased atmospheric CO2 is still lacking.

1. Introduction

A decade ago, VEMAP II (Vegetation/Ecosystem Modeling and Analysis Project Phase 2) was the first project comparing the responses of dynamic global vegetation models (DGVMs) to two transient climate change scenarios (CGCM1 and HADCM2SUL) using the Is92 emission scenario (Bachelet et al., 2003). The models simulated year-to-year variability of the carbon budget while dynamically changing the distribution of vegetation types and allowing for natural disturbance (wild fires) over the conterminous USA. Since then, there have been at least two international projects comparing DGVM responses to the same climate change scenarios over the entire globe (McGuire et al., 2001; Cramer et al., 2001). The VINCERA (Vulnerability and Impacts of North American Forests to Climate Change: Ecosystem Responses and Adaptation) project is the latest international effort comparing the response of three DGVMs (MC1, IBIS and Sheffield DGVM) to three climate change scenarios (CGCM2, HadCM3, CSIRO Mk2), and two Inter-governmental Panel on Climate Change (IPCC) emission scenarios (SRES A2 and B2). The project goal is to document the sensitivity of North American forest ecosystems to projected changes in climate. In this paper we show results from the MC1 model, comparing how results obtained with VEMAP future climate change scenarios differ from the VINCERA results over the conterminous US.

In the last 10 years, future climate change scenarios have changed. Our goal in this paper was simply to compare model results under both sets of climate scenarios to estimate the importance of changes in climate and soil inputs.

2. Methods

2.1. MC1 model

MC1 is a dynamic vegetation model (Daly et al., 2000; Bachelet et al., 2003; Lenihan et al., 2003) where biogeochemical processes are simulated using a modified version of the CENTURY model (Parton et al., 1987, 1993). A set of biogeography rules based on climatic indices and biomass determines the lifeform (broadleaf or needle-leaf, deciduous or evergreen) and the physiological type (C3 or C4 grasses). Vegetation types are defined as a unique combination of trees and grasses in a specific climatic context using the same approach that was

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Table 1
Correspondence between the DGVM vegetation types and VEMAP types

Aggregated vegetation types	VEMAP vegetation types
1. Coniferous forests	2. Boreal coniferous forest
	3. Temperate maritime coniferous forest
	4. Temperate continental coniferous forest
2. Winter deciduous forests	7. Temperate deciduous forest
3. Mixed conifer-broadleaved forests	5. Cool temperate mixed forest
	6. Warm temperate/subtropical mixed forest
4. Broadleaved evergreen	8. Tropical deciduous forest
drought-deciduous forests	9. Tropical evergreen forest
5. Savannas and woodlands	10. Temperate mixed xeromorphic woodland
	11. Temperate conifer xeromorphic woodland
	12. Tropical thorn woodland
	13. Temperate deciduous savanna
	14. Warm temperate/subtropical mixed savanna
	15. Temperate conifer savanna
	16. Tropical deciduous savanna
6. Grasslands and shrublands	1. Tundra
	17. C3 grasslands
	18. C4 grasslands
	19. Mediterranean shrubland
	20. Temperate arid shrubland
7. Deserts	21. Subtropical arid shrubland

Table 2
Comparison between average mean climatic conditions under VINCERA vs VEMAP climate change scenarios over the conterminous USA

a. Average annual historical conditions (1961–1990)

	VEMAP	VINCERA
Tmin (°C)	4.1	3.9
Tmax (°C)	18.2	18.0
T (°C)	11.1	10.9
PPT (mm)	766	739
VPR (Pascals)	875	977

b. Future conditions (2070–2100). Refer to Table 2a for units

	CGCM1	CGCM2-A2	CGCM2-B2	HADCM2SUL	HADCM3-A2	HADCM3-B2
Tmin	9.2	8.7	7.2	7.6	8.8	7.4
Tmax	23.4	23.3	21.7	20.6	23.3	21.7
T	16.3	16.0	14.5	14.1	16.0	14.5
PPT	843	728	740	924	793	781
VPR	1220	1173	1272	1109	1274	1191

developed from MAPSS, an equilibrium biogeography model (Neilson, 1995). We only show seven vegetation types simulated by MC1 to simplify the analysis of the biogeography results. The correspondence between these vegetation types and the original VEMAP types is described in Table 1. The model also includes a fire model (Lenihan et al., this issue) that simulates the occurrence, behavior and effects of wildfire. For each vegetation type, it includes specific fuel parameters (e.g., surface to volume ratio, depth to load ratio, moisture of extinction, etc.) and minimum and maximum fire return intervals (Leenhouts, 1998) to constrain the estimate of the cell fraction affected by wildfires.

The model was run on a grid using soil depth, soil texture, bulk density, percent rock fragment, monthly temperature (minimum and maximum), precipitation, and vapor pressure deficit. Grid cell calculations are independent of each other i.e., there is no exchange of information across cells. The model reads climate data at a monthly time-step but the fire module interpolates the data to create daily inputs. We use a spin-up period of 500 years to initialize the model with realistic fire

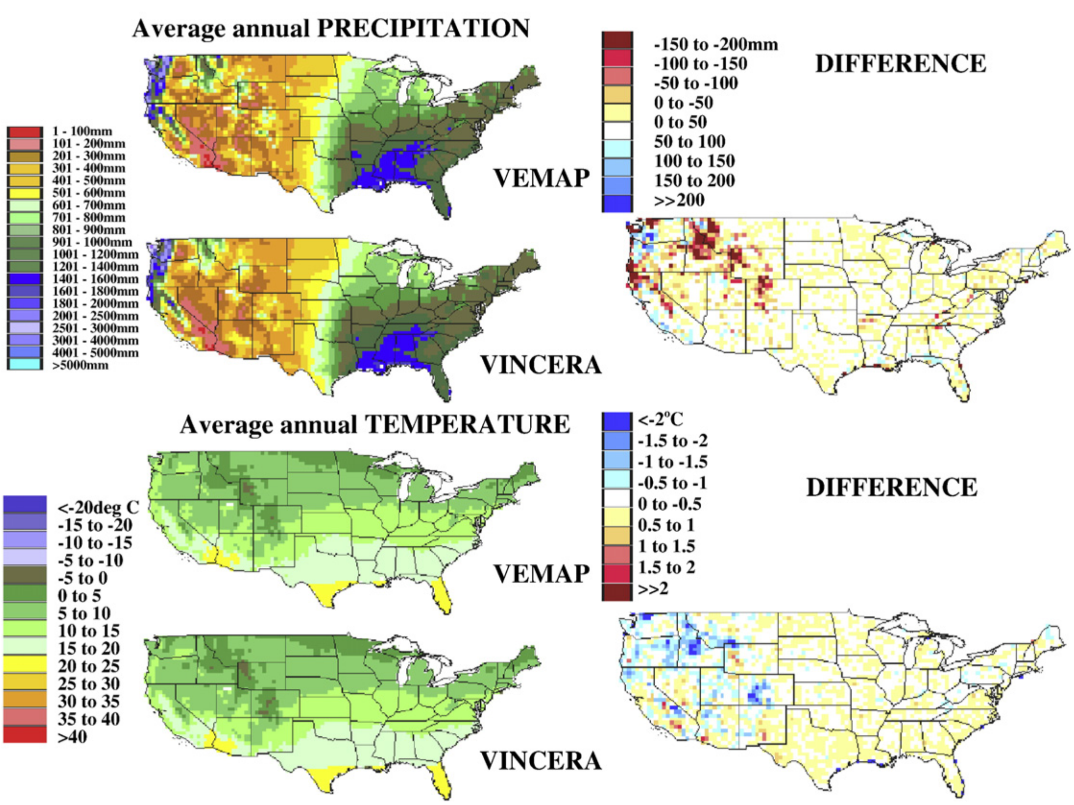

Fig. 1. Absolute values and differences between VEMAP and VINCERA historical (1961–1990) climate conditions.

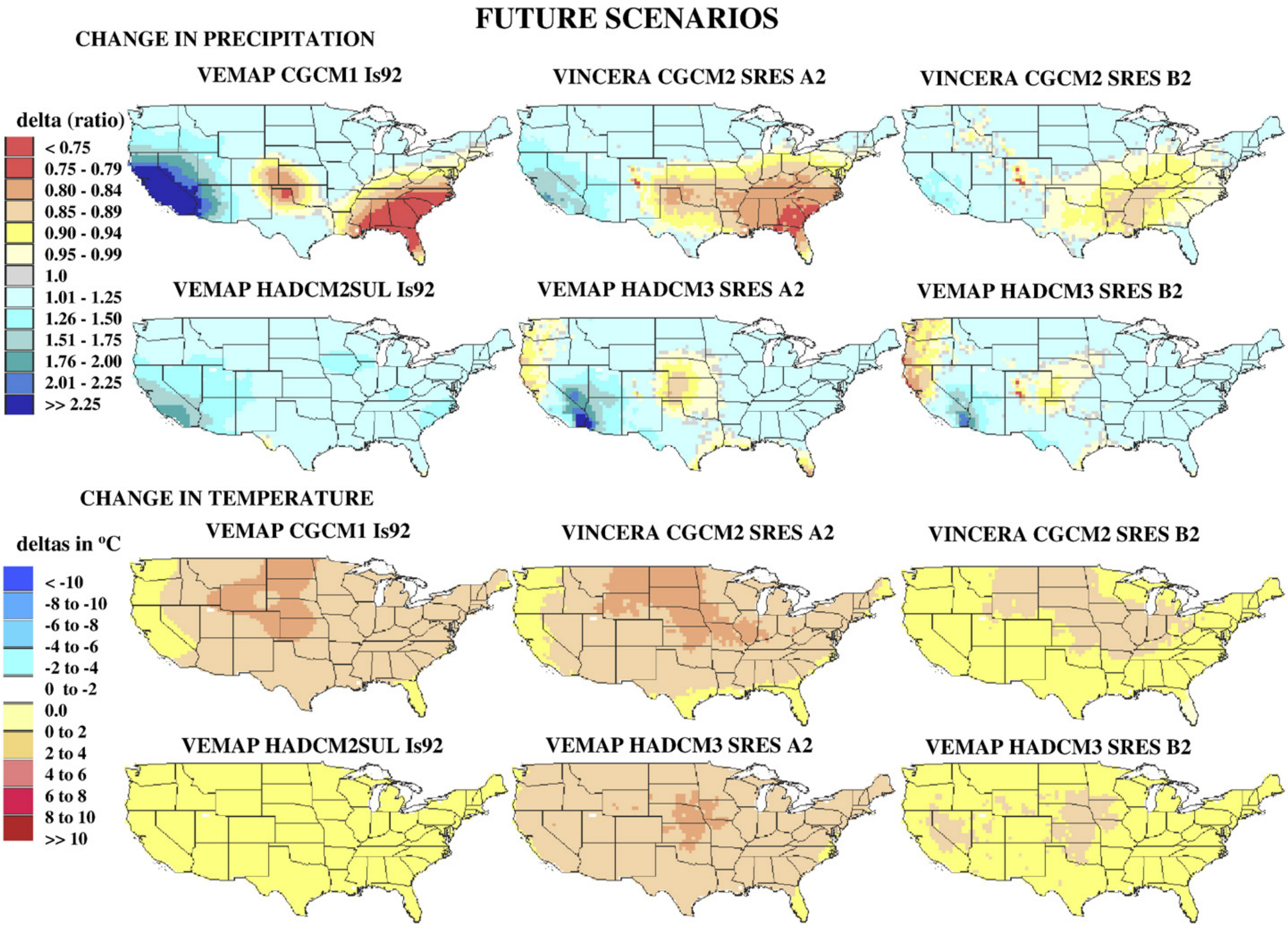

Fig. 2. Absolute change between future and historical conditions under VEMAP and VINCERA future climate scenarios.

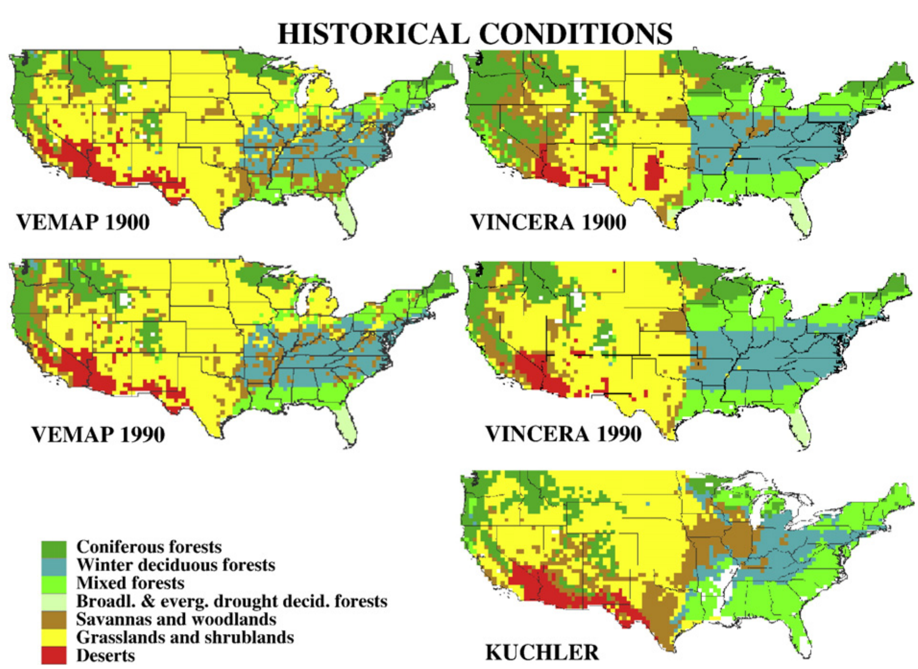

Fig. 3. Distribution of aggregated vegetation classes (modal average) simulated by MC1 under VEMAP and VINCERA historical climate compared with a map derived from Küchler (1964). The model assumes a continuous increase in the atmospheric CO_2 concentration from 295 ppm in 1895 to 354 ppm in 1990.

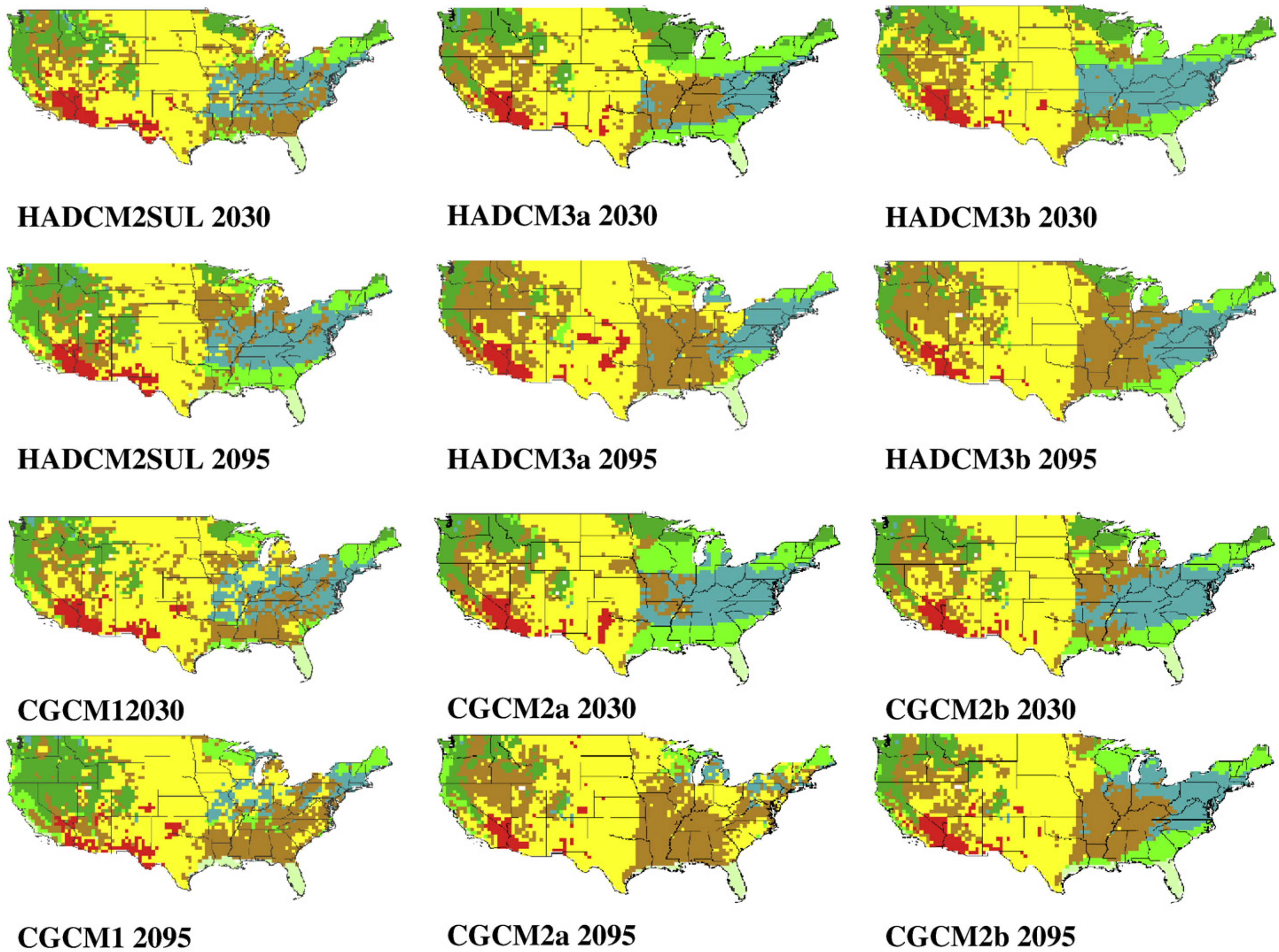

Fig. 4. Distribution of aggregated vegetation classes (modal average) simulated by MC1 under future VEMAP and VINCERA climate. The model assumes a continuous increase in the atmospheric CO_2 concentration from 295 ppm in 1895 to 712 ppm in 2100 for VEMAP, and 605 ppm under SRES A and 823 ppm under SRES B in 2100 for VINCERA.

dynamics. Spin-up is terminated when NBP[1] (net biological productivity) approaches zero. Fire occurrence is simulated as a discrete event with no more than one event per year in each cell thus only large fires are represented. There is no constraint in the model on fire occurrence due to the availability of an ignition source, such as lightning or human-caused ignition. A fire suppression switch was included in the model by calibrating the output to the observed area burned for the conterminous US since the 1950s (applying a reduction factor of 1/8 to the original area burned simulated by the model).

The model simulates potential vegetation dynamics without human-induced changes such as urbanization, agriculture, forest harvest, grazing, or air pollution. We imposed a map of agricultural and urban areas to mask out areas where there is no natural vegetation after the run was finished (Bachelet et al., 2003). The model does not simulate seed production or dispersal. The model does not include biotic disturbance agents such as pathogens or insects. Nitrogen demand is always met in MC1 but the C:N ratios of the various plant compartments are variable within limits that are fixed for each lifeform. The hydrology is a simple “bucket” type with several soil layers and only simulates saturated flow. The model does not simulate wetlands or saturated, anaerobic soils.

[1] NBP is calculated as the difference between NPP (net primary production)and heterotrophic respiration plus fire emissions.

2.2. Model inputs

2.2.1. VEMAP

In VEMAP, Kittel et al. (2004) developed common datasets for model input, including a high resolution climate history and 2 future climate change scenarios of the conterminous USA on a 0.5° latitude/longitude grid (maximum and minimum temperature, vapor pressure, precipitation) with a soils data set (soil depth, bulk density, rock fragment, soil texture). These data were provided to us by the VEMAP Data Group from the National Center for Atmospheric Research (Boulder, Colorado).

The climate change scenarios included a moderately warm scenario from the Hadley Climate Centre (Johns et al., 1997, Mitchell and Johns, 1997) – HADCM2SUL – (3.2 °C increase in annual average U.S. temperature from 2000 to 2100) and a warmer scenario (5.8 °C increase in annual average U.S. temperature from 2000 to 2100) – CGCM1 – from the Canadian Climate Center (Boer et al., 1999a,b, Flato et al., 1999). Both transient scenarios started in 1895 and ran to the present using observed CO_2 increases (Schimel et al., 2000). They used IPCC projections of gradual (1% y^{-1}) future greenhouse gas concentrations (IS92a) (Kattenberg et al., 1996) in the future such that CO_2 atmospheric concentration reached 712 ppm in year 2100. A 100-year spin-up climate time series was created by detrending long-term monthly precipitation and temperature records using a 30-year running average high-pass filter and adjusting the means to the first 15 years of the historical record (1895–1909) (Kittel et al., 2004).

2.2.2. VINCERA

In the VINCERA project, McKenney et al. (2004) developed the climate (Tmax, Tmin, VPR, PPT) and soils (soil depth, bulk density, rock fragment, soil texture) dataset for North America on a 0.5° grid. Soils data were compiled from available sources: the Canadian Soils Information System (CanSIS) Soil Landscapes of Canada (SLC) Version 2.2 database, the U.S. VEMAP soils data set and the Alaskan State Soil Geographic (STATSGO) data set. For each climate and soil variable, ANUSPLIN was used to generate regular grid spatial models.

Climate change scenarios were developed at a resolution of 0.5° latitude/longitude for North America with two greenhouse gas (GHG) emission scenarios, SRES A2 and B2 (Price et al., 2004). Data from the Canadian Global Climate Model (CGCM2) were obtained from the Canadian Climate Centre for Modelling and Analysis, while data from the UK Hadley Climate Centre GCM (HadCM3) were obtained from the IPCC Data Distribution Report to CCIAP Centre (IPCC DDC). Details on the climate scenarios can be viewed interactively at http://www.glfc.cfs.nrcan.gc.ca/landscape/climate_models_e.html.

Time series of historical and projected changes in atmospheric CO_2 used in the IPCC A2 and B2 emissions scenarios were obtained from Ron Stouffer at GFDL, Princeton, NJ.

Processing the GCM output data followed the approach used for VEMAP (VEMAP Members, 1995) and is described in greater detail in Price et al. (2004). A 100-year spin-up climate time series was created by detrending long-term monthly precipitation and temperature records using a 30-year running average high-pass filter and adjusting the means to the first 15 years of the historical record (1901–1914) following VEMAP procedure.

3. Results

3.1. Climate comparison

Historical climate varied slightly between the two projects. VINCERA historical climate was slightly cooler and drier than VEMAP historical climate (Table 2a) especially in the western US (Fig. 1). In a recent paper, Daly (2006) compared most commonly used interpolation methods including ANUSPLIN and PRISM approaches to create climate datasets. He acknowledged that spatial climate data sets are “a significant source of error in any analysis that uses them as input”. He also added that “there is no one satisfactory method for quantitatively estimating error in spatial climate data sets, because the field that is being estimated is unknown between data points”. It is thus difficult in this paper to assert the reliability of either datasets because of the coarse resolution of the dataset that was created and the lack of “ground truth” in such complex terrain as the western USA.

Future climate scenarios include large changes in climate conditions with regard to historical means by the end of the 21st century. Mean annual temperature increased by 47% under both CGCM1 and CGCM2-A2 but mean annual precipitation increased by 10% under CGCM1 while it slightly decreased under CGCM2-A2 (Table 2b and Fig. 2). The large increases in precipitation simulated

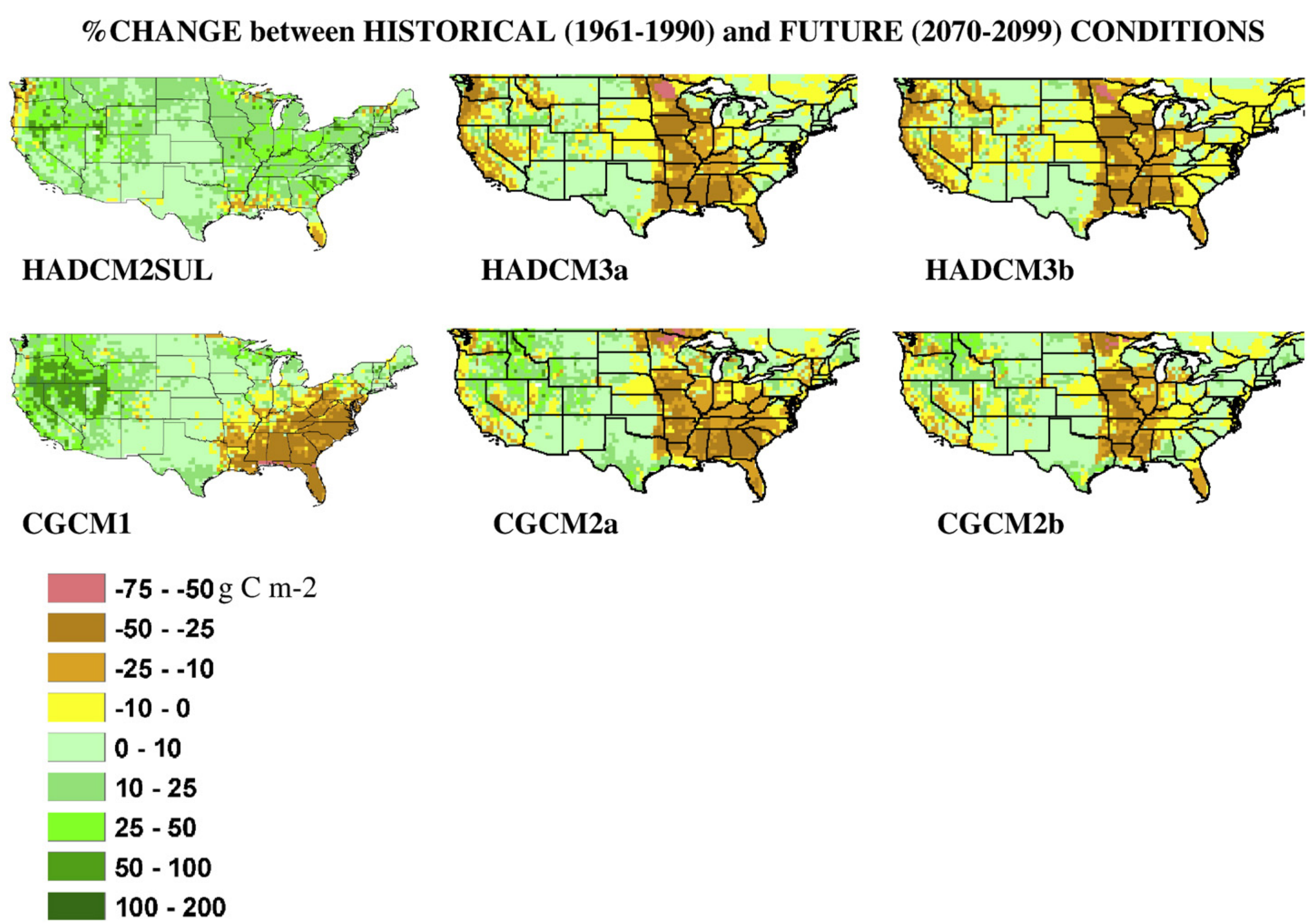

Fig. 5. Change in total carbon storage simulated by MC1 under VEMAP and VINCERA from 1895 to 2100. The model assumes a continuous increase in the atmospheric CO_2 concentration from 295 ppm in 1895 to 712 ppm in 2100 under VEMAP, 605 ppm under SRES A and 823 ppm under SRES B in 2100 for VINCERA.

over California under VEMAP scenarios did not occur with the newer scenarios. Under CGCM2-B2, increases in temperature were lower (33%) and decreases in precipitation in the SE were more moderate than under CGCM1 but the region affected was larger (Fig. 2). Under HADCM3, average annual temperature increased (33–47%) more than under HADCM2SUL (27%) while precipitation increased more moderately (6–7%) than under HADCM2SUL (21%) (Fig. 2). Projections of drier conditions in the Pacific Northwest region and the Great Plains under both HADCM3 scenarios did not occur under HADCM2SUL. Similarly HADCM3 showed an increase in precipitation in southern California–Arizona that was not projected under HADCM2SUL.

3.2. Vegetation distribution

3.2.1. Historical climate

We compared the vegetation distribution simulated for 1900 and 1990 under VEMAP and VINCERA to Küchler's (1964) potential vegetation map (Fig. 3). Küchler's map of the conterminous US remains the best available potential vegetation map for the middle of the 20th century. The model captures the broad patterns of vegetation distribution across the United States including the eastern deciduous forests, the western coniferous forests, the central Great Plains and the Desert Southwest. However, there are large differences between vegetation distribution simulated under VEMAP versus VINCERA

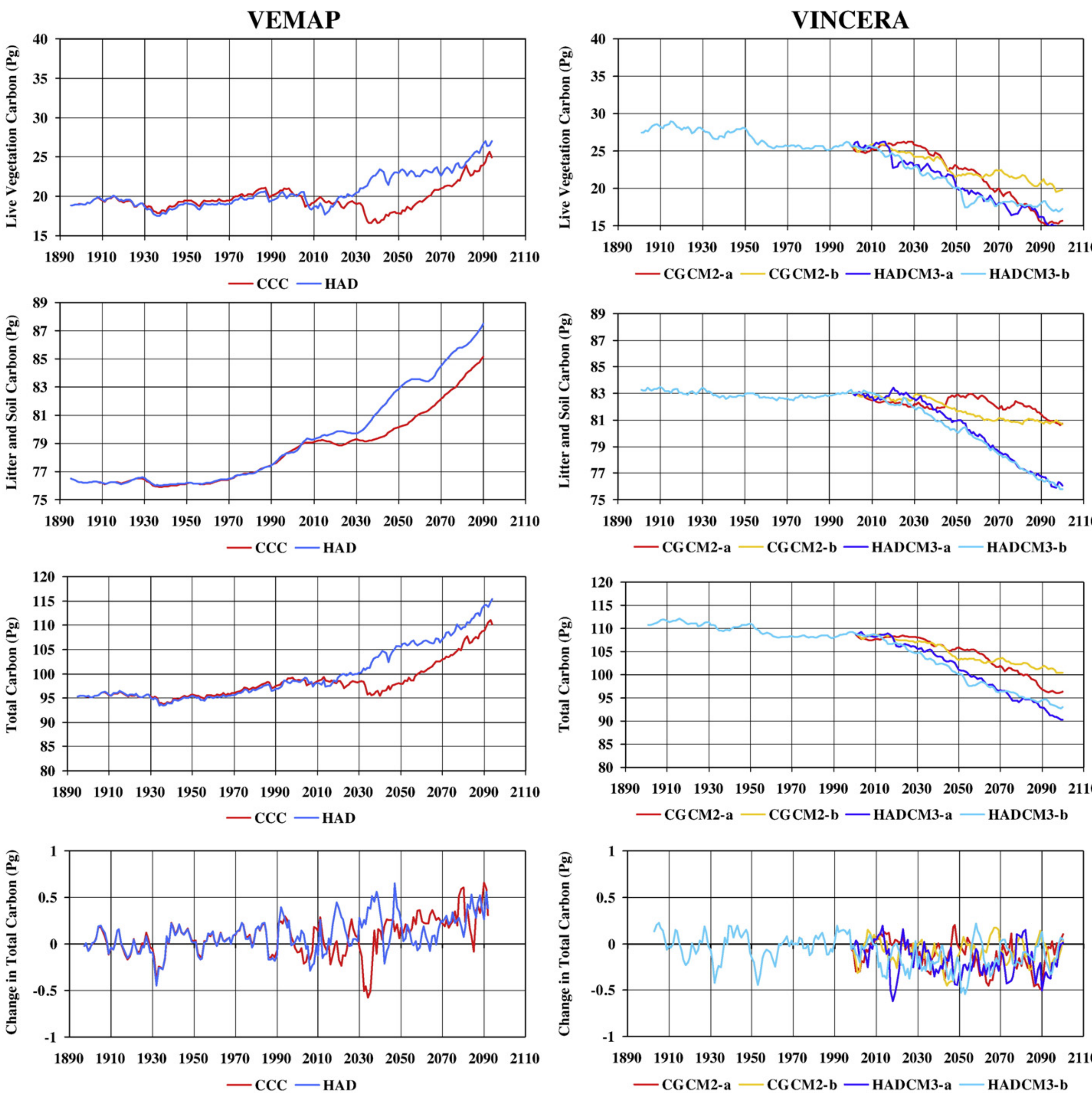

Fig. 6. Total ecosystem carbon, live vegetation and soil carbon, and NBP simulated by MC1 from 1895 to 2100, under VEMAP and VINCERA. The model assumes a continuous increase in the atmospheric CO_2 concentration from 295 ppm in 1895 to 712 ppm in 2100 under VEMAP and 605 ppm under SRES A and 823 ppm under SRES B in 2100 for VINCERA.

climate conditions and there are several areas of disagreement between the model results and Küchler's map. MC1 simulates grasslands in the Prairie Peninsula region south of the Great Lakes under VEMAP climate and forests under VINCERA climate where Küchler shows savannas and woodlands. The model also fails to simulate the grasslands of central California and the extensive deserts of southern New Mexico and west Texas under VINCERA climate. The model simulates deciduous rather than mixed forests in the Carolinas under both VINCERA and VEMAP historical climate. The greatest lack of agreement between the model simulations and Küchler's map occurs in savannas of Texas, Illinois, Iowa and Missouri. Some of the mismatch can be partially explained by the role of fire in the model. There is a continuous shift between savannas and grasslands as the woody component disappears after each fire occurrence. In drought-prone areas such as the Great Plains where fire returns frequently, this shift can be particularly frequent.

3.2.2. Future climate

Under all scenarios, the interior West grasslands shift to savannas and woodlands by 2030 (Fig. 4). Under both CGCM1 and HADCM2SUL, the eastern mixed forest shift to savannas and woodlands by 2030. Under HADCM3-A2 and to a lesser extent CGCM2-A2 the western edge of the eastern deciduous forests shift to savannas and woodlands while the western edge of the mixed forests does so under the SRES B2 CO_2 scenarios. By 2095, CGCM1, CGCM2 and HADCM3 all show large forest shifts to savannas and woodlands throughout the Midwest, opening up to grasslands under CGCM2-A2 and a large extension of woodlands in the interior West (Fig. 4). Under both VEMAP and VINCERA scenarios, the largest vegetation expansion is that of woodlands and savannas between 1961–1990 and the last 30 years of the 21st century (Table 2), and the largest decreases in area occur first in boreal forests and C3 grasslands because of the warming trend, and secondly in temperate arid shrublands because of the increase in moisture in the west.

3.3. Carbon budget

Regional changes in carbon storage across the conterminous US follow the changes in vegetation cover (Fig. 5). As forested areas shift to savannas and woodlands, carbon losses occur in the eastern part of the USA and the Southeast under the VINCERA future climate scenarios and under CGCM1. As forests expand in the interior West, increases in carbon storage are simulated under both VEMAP future climate scenarios but increases are limited to smaller areas of the western states under CGCM2-A2 and B2.

MC1 simulates future increases in country-average live vegetation carbon pools (from 20 to 25 Pg) from 2030 to 2100 under both VEMAP future climate scenarios despite a decrease in the late 2030s under CGCM1 (Fig. 6). Under all VINCERA scenarios, vegetation carbon decreases by 5–10 Pg by 2100. Similarly the model simulates an increase in soil carbon of about 4–6 Pg under VEMAP future climate but a decrease of up to 8 Pg under VINCERA future climate scenarios, with the largest declines under HADCM3 (Fig. 6).

Since the changes in total carbon storage vary considerably from year to year, we used a 5-year running average value to report the carbon source and sink strength (net biological productivity or NBP) of the conterminous U.S. through time (Fig. 6, bottom panel). During the drought of the 1930's, the model simulates a carbon source of about 0.4 Pg y^{-1} for both VEMAP and VINCERA historical climate conditions. Under VINCERA climate, the model simulates another source of about 0.4 Pg C y^{-1} during the drought of the 1950's. The model projects mostly a U.S. carbon sink (positive NBP) under VEMAP future climate scenarios except in the 2030s under CGCM1 when it simulates a

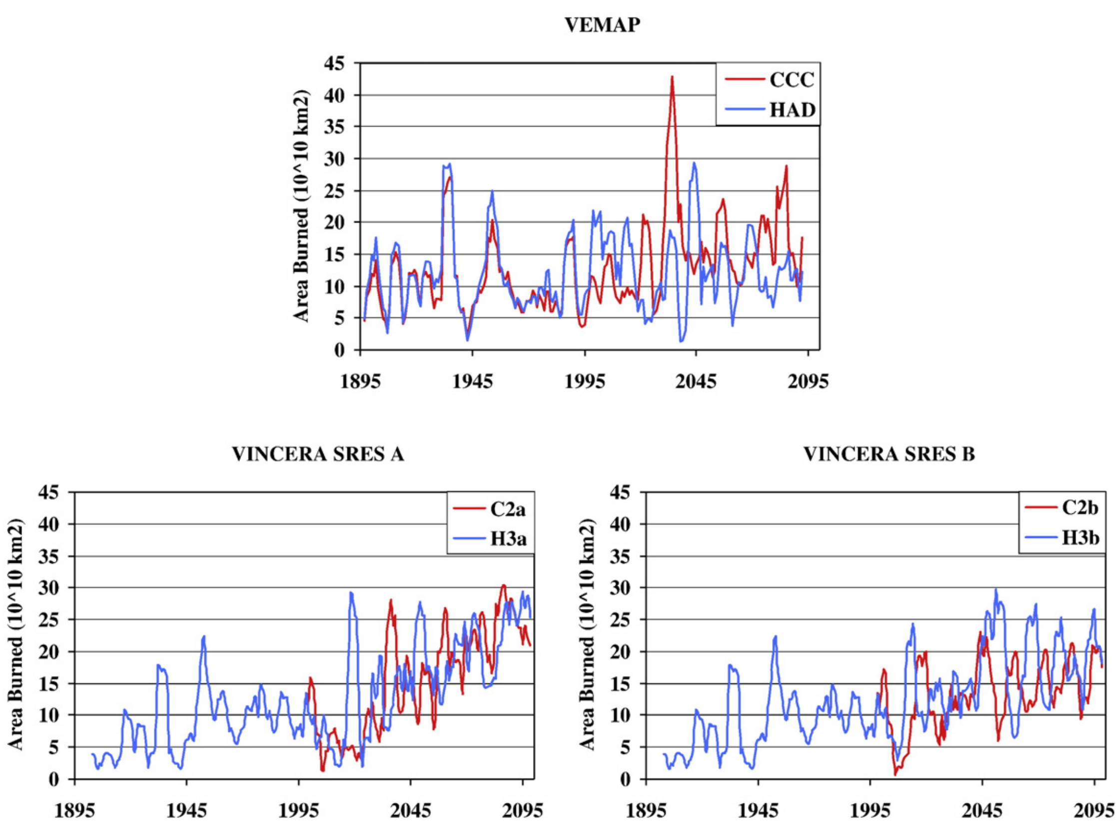

Fig. 7. Total area burned by wildfire simulated by MC1 from 1895 to 2100 under VEMAP and VINCERA climate conditions. The model assumes a continuous increase in the atmospheric CO_2 concentration from 295 ppm in 1895 to 712 ppm in 2100 under VEMAP and 605 ppm under SRES A and 823 ppm under SRES B in 2100 for VINCERA.

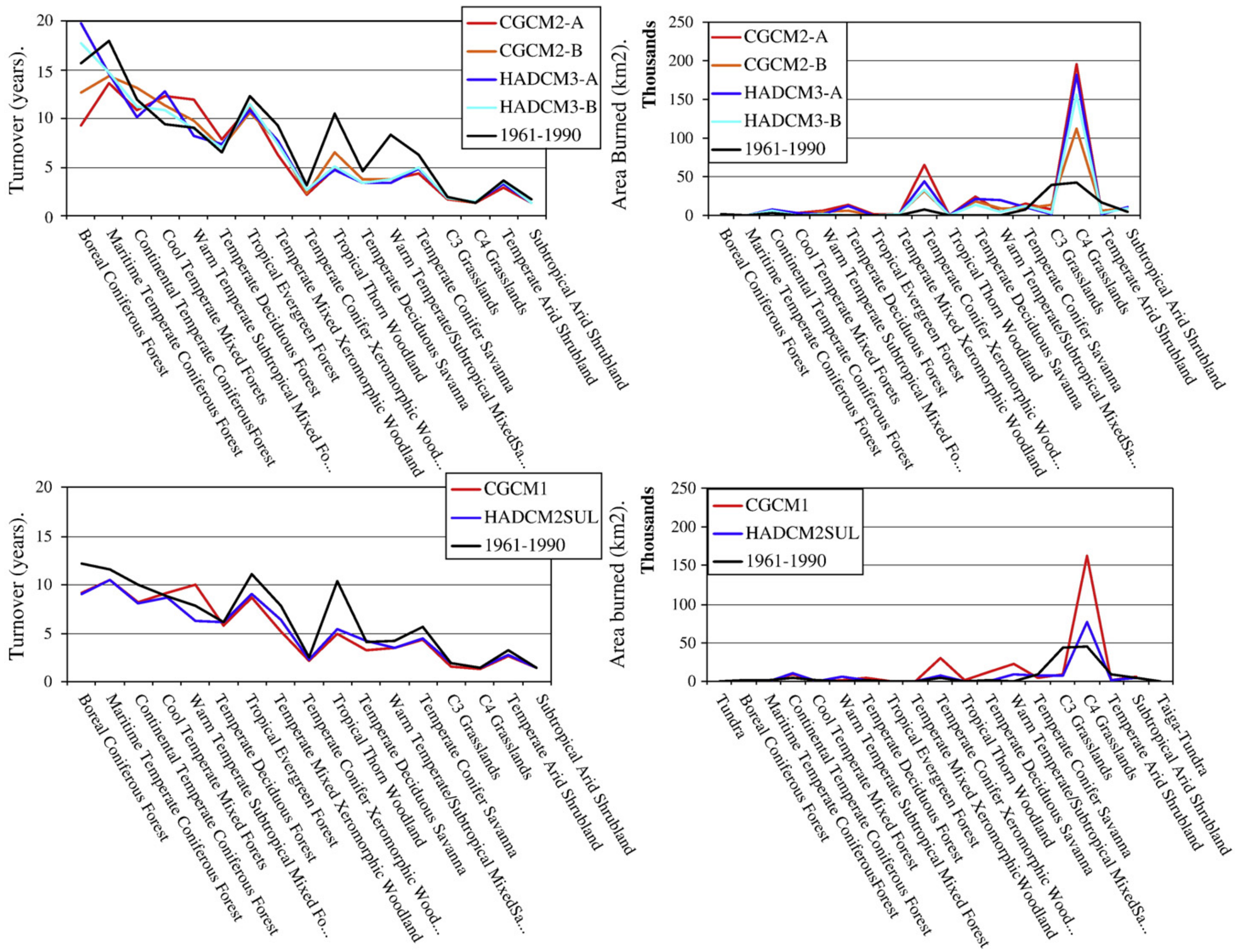

Fig. 8. Carbon turnover and area burned per vegetation types under VINCERA and VEMAP scenarios.

source of about 0.5 Pg C y^{-1}. Under VINCERA future climate, MC1 projects mostly a U.S. carbon source (negative NBP).

3.4. Fire

During the drought of the 1930's and the 1950's, the model simulates an increase in area burned for both VEMAP and VINCERA historical climate conditions (Fig. 7). The area burned by wildfires increases under all future climate scenarios but the patterns are quite different between VEMAP and VINCERA. There is a sharp increase under the VINCERA SRES A scenarios, a more moderate increase under the SRES B scenarios. The fire frequency increases after 1995 under both VEMAP scenarios but the magnitude of the area burned is larger under CGCM1 than any of the other future climate scenarios while that under HADCM2SUL is smaller than under any other scenario. Under both sets of climate scenarios, most of the fires occur in C4 grasslands and, under all VINCERA scenarios, in temperate conifer xeromorphic woodlands where VINCERA precipitation projections are less than under VEMAP (Fig. 8).

3.5. Turnover

We estimated the carbon turnover by vegetation type by calculating the ratio of live vegetation carbon to net primary production (NPP) (McGuire et al., 2002). Rates vary between 10 and 20 years for coniferous forests and 1–2 years for grasslands during the historical period. Between 1961 and 1990, the annual area burned was greatest for C4 grasslands and consequently, biomass turned over quickly in comparison with other vegetation types (1.34 years). In contrast, the smallest area burned occurred in maritime forests where we calculated a turnover rate of almost 18 years.

Under the various future climate scenarios, turnover rate decreases particularly in the woodland and savannas vegetation types where future drought conditions cause an increase in the area burned (Fig. 8).

4. Discussion

4.1. Can we validate historical carbon levels simulated by the model?

We have compared model results with published NPP observations at different sites across the US. On a per-area basis, the model agrees fairly well with the observations (Tables 3 and 4) even though it tends to overestimate savanna productivity and underestimates grassland productivity. At the ecosystem scale where most measurements occur, carbon losses due to disturbance such as fires are infrequent and difficult to quantify and can explain the discrepancy between field observations and model results. At the country scale where our model is run, fire can significantly affect vegetation and carbon dynamics that are not

Table 3
Comparison between the average NPP simulated by MC1 between 1961 and 1990 and observed NPP from two sources: estimated total NPP using LTER–ANPP records (Knapp and Smith 2001) and above to belowground production ratio calculated by Gower et al. (1999), mean observed NPP as collected by R. Olson (Oak Ridge National Lab., pers. comm.) and cited in Jager et al. (2000). (HF = Harvard Forest, MA; HB = Hubbard Brook, NH; CEDAR CREEK, MN; KONZA = Konza Prairie, KS; CPER = Central Plains Experimental Range, CO; SEV = Sevilleta, NM; JOR = Jornada, NM)

NPP in Pg C y^{-1}	MC1	LTER–ANPP	LTER–NPP	OAK RIDGE DATASET
	Mean (SD)	Mean (SE)	Mean	Mean (SD)
Coniferous forests	0.28-VI 0.22-VE			Boreal: 0.32 (0.19) Temperate maritime: 0.69 (0.28) Temperate continental: 0.61 (0.24)
Winter deciduous forests	1.35-VI 1.00-VE	HF – 0.75 (0.02) HB – 0.71 (0.01)	0.88 1.27	0.60 (0.28)
Mixed forests	0.54-VI 0.36-VE			Cool temperate: 0.55 (0.12)
Savannas	0.06-VI 0.15-VE	CEDAR CREEK – 0.28 (0.02)	0.44	
Grasslands	0.45-VI 0.71-VE	KONZA – 0.44 (0.02) CPER –0.12 (0.01) SEV– 0.19 (0.02)	0.71 0.19 0.30	Tundra: 0.09 (0.06) C3: 0.35 (0.25) C4: 0.47 (0.24)
DESERTS	0.09-VI 0.09-VE	JOR – 0.23 (0.02)	0.40	Arid shrub: 0.13 (0.08) 0.06 (0.04)

recorded at LTER, Ameriflux or FACE sites. At that scale, NBP is the most appropriate way to analyze long-term large-scale changes in carbon fluxes and pools but little data has been published for the United States (Boisvenue and Running, 2006). Pacala et al. (2001) summarized and reconciled the most recent results from various studies and came up with a carbon sink estimate of 0.30 to 0.58 Pg C y^{-1} for the conterminous USA (Table 5). For this study, we estimated a carbon sink of 0.02 Pg C y^{-1} between 1981 and 1990 and 0.04 Pg C y^{-1} between 1991 and 2000 for all non-agricultural land in the conterminous US. So by including a realistic fire model, we estimated a much lower US carbon sink due to natural vegetation than other models have come up with so far.

4.2. How much difference is there between the results from the 2 projects?

Differences between simulation results obtained under the two sets of climate scenarios were surprisingly large even during the historical period (1961–1990). The model projected carbon gains on average across the entire conterminous US with the VEMAP future climate scenarios but significant losses under all the VINCERA scenarios (Fig. 6). VINCERA future climate is projected to be warmer and drier than VEMAP future climate and most of the eastern forests are compromised (Fig. 5) while significant declines occur in the West

Table 4
Comparison between the mean annual aboveground net primary production (ANPP) simulated by MC1 between 1961 and 1990 and observed mean ANPP for US Long Term Ecological Research (LTER) sites (Huxman et al., 2004) and mean NPP observations (Turner et al., 2005). Values for the ratio of root to total NPP from Gower et al. (1999)

NPP (g c m^{-2} y^{-1})	LTER–ANPP sites	Mean ANPP (SD)	TNPP MC1 results (TNPP;root/TNPP)
Coniferous forests	H.J. Andrews, Oregon Metolius, Oregon	612.8 (72.9) 356	663 (839;0.21) 611 (VE:774;0.21)
Winter deciduous forests	Harvard Forest, MA	744.5(47.8) Deciduous: 679 Conifer: 552	795 (970;0.18) 820 (VE:1000;0.18)
	Hubbard Brook, NH	704.5 (24.5)	
Mixed forests			888 (TNPP) 867 (TNPP-VE)
Savannas	Cedar Creek, Minnesota	277.3 (91.9)	518 (TNPP) 545 (TNPP-VE)
Grasslands	Jasper Ridge, California Sevilleta, New Mexico	487.6(78.3) 184.5 (46.4) 54	167 (417;0.6) 186 (VE:465;0.6)
	CPER, Colorado Konza Prairie, Kansas Kellog, Michigan	116.5 (39.7) 442.6 (107.4) 431.0 (106.1)	
Deserts	Rock Valley, Nevada Jornada, New Mexico	28.1(34.3) 229.1 (64.0)	72.5 (290;0.75) 149 (VE:597;0.75)

Table 5
Estimates of Net Biological Production from recent sources for the conterminous US

Reference	Time period of study	Geographic area	Method	NBP (Pg C y^{-1})
Fan et al. (1998)	Early 1990s	USA	Inverse modeling	0.81
Birdsey and Heath (1995)	1980–1990	USA	Forest inventory	0.31
Turner et al. (1995)	1980–1990	USA (forests)	Biogeochemistry model	0.08
Brown and Schroeder (1999)	1980s	Eastern US (forests)	Forest inventory	0.17
Goodale et al. (2002)	1980–1990	USA	Forest inventory and model	0.28
Schimel et al. (2000)	1980s	USA	3 Biogeochemistry models	0.08
Potter and Klooster (1999)	1983–1987	30–60°N lat.	Biogeochemistry model (NASA-CASA)	0.4–2.6
Houghton et al. (1999)	1980–1990	USA	Book-keeping model	0.35
Houghton and Hackler (2001)	1980–1990	USA	Book-keeping model	0.12
Pacala et al. (2001)	1980–1990	USA	Forest inventory	0.30–0.58
McGuire et al. (2002)	1980–1990	USA	DGVMs (LPJ, IBIS)	0.08–0.25
This study	1981–1990 1991–2000	USA	DGVM (MC1)	0.02 0.04

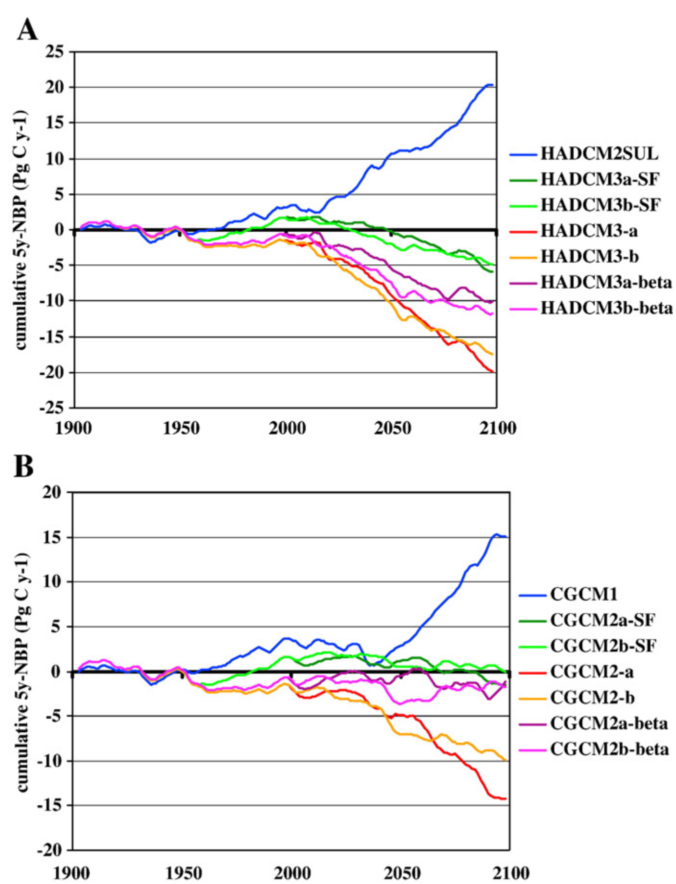

Fig. 9. Total carbon storage simulated by MC1 under VINCERA with a low (A) and a high (B) CO_2 enhancement effect.

(Lenihan et al., this issue). It is a bleaker picture of the future that emerges from these new runs. Even a large CO_2 growth enhancement, which has only been demonstrated in young stands of temperate forests, is not capable of mitigating the climate stress on ecosystems (Fig. 9).

4.3. The importance of the CO_2 effect

Assumptions about CO_2 enhancement of net primary production can greatly affect projections of carbon storage by the terrestrial biosphere. Because carbon uptake is not saturated under current atmospheric CO_2 concentrations (Long et al., 2004), NPP is widely assumed to be increasing as atmospheric CO_2 continues to increase. Experimental data have extensively documented the physiological mechanisms of plant response (Long et al., 2004) and have been used to calibrate models to enhance productivity and water use efficiency in a CO_2-rich future. However, most of the early experiments were performed in controlled laboratory or greenhouse conditions and hypotheses about acclimation and nutrient availability thresholds in mature forests growing in natural conditions were put forward. New stand level experimental results show a median increase of 23% in NPP recorded at four FACE experimental sites where young forest stands were exposed to elevated (550 ppm) and compared with ambient (370 ppm) CO_2 (Norby et al., 2005). Using this figure, Boisvenue and Running (2006) estimated that, assuming a linear interpolation from the 1950s until today, there should have been a 4% increase in NPP in forest ecosystems. However, Caspersen et al. (2000) showed no evidence of any growth enhancement from CO_2 fertilization in various forests along a latitudinal gradient in the eastern United States from 1930 to 1980. Moreover, Körner et al. (2005) found an increased tolerance to drought stress and an enhancement of carbon flux in mature temperate forests but no overall growth stimulation after 4 years at higher CO_2 levels. To illustrate the impacts of this enhancement effect on carbon budget projections for the USA, we ran the MC1 model with a low (about 10% increase in NPP at 550 ppm) and a high (about 20% increase in NPP at 550 ppm) CO_2 enhancement effects and compared results. While under all VINCERA scenarios the model projects a decrease in NBP, the growth enhancement effect reduces carbon losses by about 10 Pg C y^{-1} especially under the CGCM2 scenarios (Fig. 9). Given the sensitivity of the model to the CO_2-induced growth enhancement factors and the lack of long-term experimental results in mature forests, more research will be necessary to establish the credibility of model projections of faster forest growth and carbon storage.

5. Conclusion

Differences between VEMAP and VINCERA climate scenarios occur both under historical and future climate conditions. The more recent VINCERA projections are more stressful for the western United States where VEMAP scenarios projected increases in precipitation but also for the Midwest and eastern forests in general. Simulations show that grasslands tend to be replaced by woody vegetation in the interior West while drought stress opens up the canopy in the eastern U.S. allowing the replacement of forests by grassier vegetation types. Projected carbon storage on a country-wide basis is very sensitive to the CO_2 growth enhancement factor used in the model reducing carbon losses by about 50% when the NPP enhancement is doubled. While under the earlier VEMAP scenarios the United States were a carbon sink, under the VINCERA scenarios the country becomes a source of 10–20 Pg C y^{-1} under the most stressful scenarios. Until climate change scenarios converge on a common future scenario and the importance of the CO_2 fertilization effect on mature ecosystems has been clarified, projections of natural ecosystem response to future climate will continue to oscillate in magnitude between a carbon sink or a source enhanced by the increased occurrence of fires in a warmer world.

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